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Detection of Artificial Sources of Nuclear Radiation in Space

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19 ABSTRACT (Continue on reverse if necessary and identify by block number)

The γ-ray experiment on board NASA's Solar Maximum Mission Satellite (SMM) has detected nuclear radiation emitted from the reactor on COSMOS 1176. Direct observations of γ-rays and possibly neutrons from this reactor have been made at distances as close as ~ 350 km. Nuclear line features have been observed in the γ-ray spectrum. Explanations for some of these features are presented. The absolute power of the reactor is difficult to estimate at present; however, there is evidence that both the intensity and spectral shape of the emitted radiation changed significantly during the operational period of COSMOS. The reactor was also

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19. ABSTRACTS (Continued)

detected at distances of ≥ 6,300 km in an indirect manner. Positrons and electrons escaping from the COSMOS spacecraft following production by the intense γ-radiation are stored temporarily in the Earth's magnetic field and unambiguous signal due to their characteristic annihilation into γ-rays at 511 keV. Details of these observations and their implications are discussed.

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DETECTION OF ARTIFICIAL SOURCES OF NUCLEAR RADIATION IN SPACE

I. INTRODUCTION

Nuclear radiation emitted by COSMOS 1176 has unexpectedly been detected by a gamma-ray instrument on board NASA's Solar Maximum Mission Satellite (SMM). Three different kinds of events were observed. When SMM was within approximately 500 km of COSMOS 1176, gamma rays and possibly neutrons from its nuclear reactor were detected. At other times and at ranges of 800 to 6000 km, positrons and electrons produced in the outer layer of COSMOS 1176 were detected. These detections occurred when the two satellites were located on the same geomagnetic field lines along which the charged particles travelled. The positrons were identified by the 0.51 MeV γ-rays which were produced when they annihilated in the SMM spacecraft.

In Section II we describe the general background and history of how these phenomena were discovered and the instrumentation used. In Section III we describe the observations of both the direct γ-ray spectrum from the reactor, and the positron and electron events. Section IV provides an interpretation and implications of the data. Sections V & VI discuss the further work that is being done with the SMM data base to assess the security implications of the COSMOS 1176 capability.

II. BACKGROUND

The Solar Maximum Mission Satellite was conceived by NASA to study solar flares over the broadest range of frequencies possible. It therefore included instrumentation sensitive from the optical range to energies in excess of 100 MeV in the gamma ray region of the electromagnetic spectrum. The satellite was launched in February 1980 in order to take advantage of the current maximum in the 11 year solar activity cycle.

A. COLLABORATION

The gamma ray experiment which has provided the data on which this work is based is a collaborative effort between three institutions. The lead institution is the University of New Hampshire where most of the initial design and testing was done. This group is under the direction of the Principle Investigator Prof. E.L. Chupp. The other primary scientific personnel are Drs. D.J. Forrest and J.M. Ryan. The

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second institution is the Max Planck Institute for Extra-terrestrial Physics and Astrophysics in Garching, West Germany. The scientific personnel most involved in this work are Drs. E. Rieger, C. Reppin, and G. Kanbach. This group was responsible for the mechanical design and fabrication of the detector. The NRL participation in this experiment has been concentrated in the areas of modeling the instrument's response function and performing detailed data analysis on the production tapes obtained from NASA. Drs. G. Share, J. Kurfess, R. Kinzer, N. Johnson and M. Strickman have been the principle NRL participants.

B. INSTRUMENT DESIGN AND CAPABILITIES

Details of the experiment can be found in Forrest et. al. (1980). A schematic drawing of the detector is shown in Fig. 1. The basic elements for detecting incident gamma-radiation are seven 3"x3" NaI(Tl) detectors. These detectors are summed together to provide a geometric area of 320 cm^2 which is sensitive over a range in energies from 250 keV to about 100 MeV. Pulse height spectra are accumulated over 16 sec intervals with an energy resolution of about 7 percent at the 662 keV gamma-ray of ^{137}Cs. These seven central detectors are shielded from background gamma-rays by a 1" thick annulus made of CsI and a 3" thick back disk of CsI. The annulus is ~30% transparent and the back disk is ~3% transparent at 500 keV. Front and back plastic shields reject charged particles entering the aperture. The forward aperture has a field of view of ~2π steradian. The satellite is 3-axis stabilized and is accurately pointed (to within arc secs) in the Solar direction at all times. Due to its location on the spacecraft only one of the detector's sides has relatively little interfering material, while the other three are adjacent to other instruments (see Fig. 2). The spacecraft control systems are located in the rear of the detector. These different spacecraft elements represent a complex shielding pattern and make conclusions about radiation incident from directions away from the forward aperture difficult to assess.

More precise time resolution than 16.38 s is available (64 ms) in a 50 keV band near 300 keV. The experiment also incorporates two 7 cm^2 X-ray detectors sensitive in the 10-140 keV energy region and having a temporal resolution of 1 sec. There is one other instrument on board SMM which is capable of providing high quality X-ray spectral information. This is the Hard X-Ray Burst Spectrometer which is sensitive in the 25-500 keV energy range. Two broad channels of this detector (sensitive primarily to charged particles) are available on the NRL data tapes.

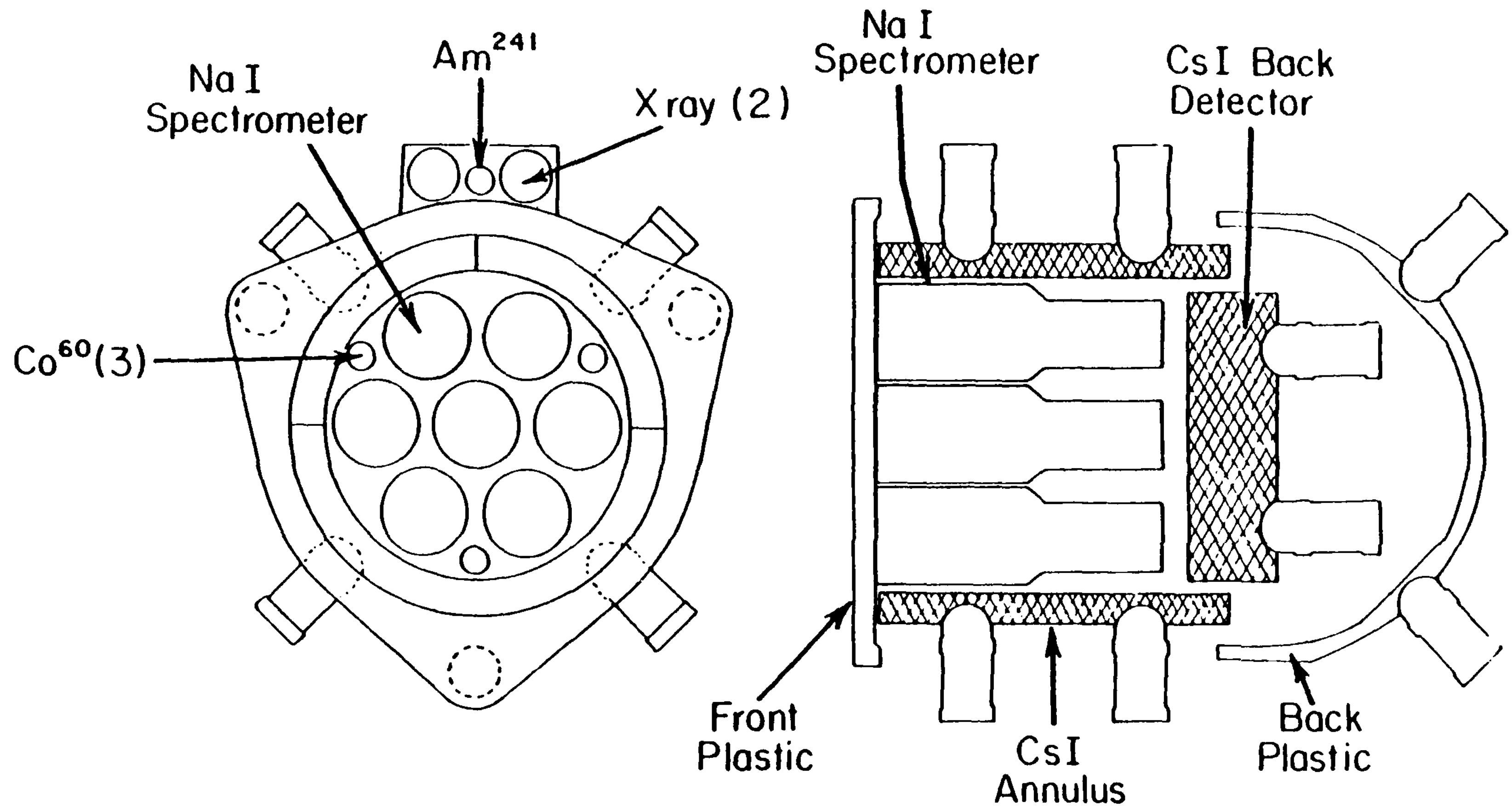

Fig. 1 — Schematic drawing of the gamma-ray experiment on SMM. Co^{60} and Am^{241} are calibration sources.

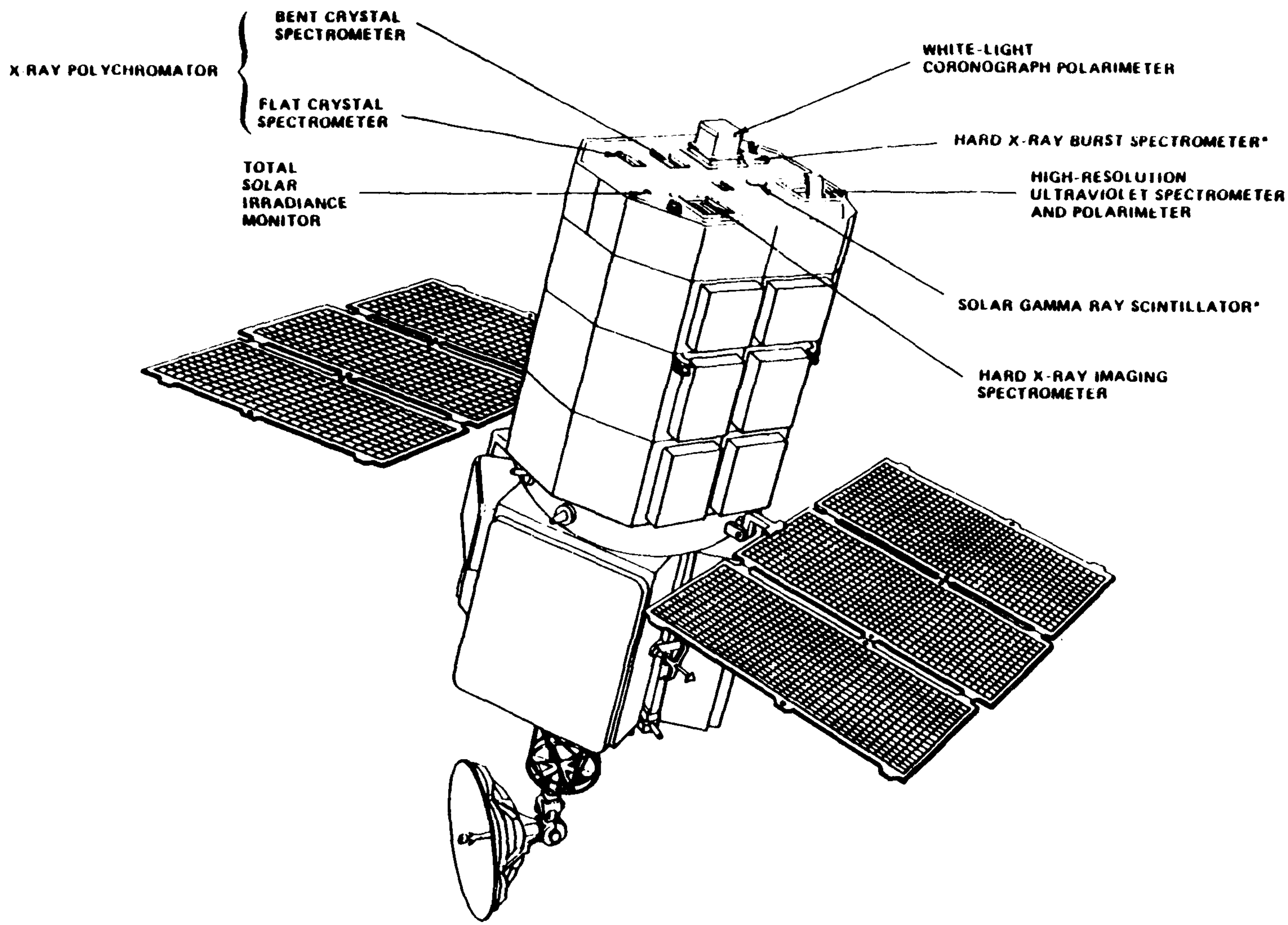

Fig. 2 — Layout of the experiments on the SMM spacecraft. The gamma-ray experiment lies below the skin of the satellite in the specified position.

Production data analysis of SMM data has proceeded in a timely manner. Data from the February launch through the beginning of May 1981 have been processed. Part of the processing involves the production of archival microfilm. This archival film is useful in analyzing specific energetic events identified in the production analysis. These events are detected using an algorithm which automatically searches the data in the archival plots for bursts or transient features. This capability was employed to great advantage in discovering and investigating the three forms of nuclear radiation detected from COSMOS 1176.

In Fig. 3 are plotted the rates obtained in various γ-ray energy windows during an orbit on May 8, 1980. For the first 3000 sec, the Sun is in the field of view. After that time the satellite moved behind the Earth. An instrument calibration then was performed. The increased rates observed from 350 keV to 10 MeV following the calibration are due to the observation of nuclear radiation emitted by the reactor of COSMOS 1176 as it passed below SMM in the field of view of the gamma ray detector. The earlier spike near 700 sec in the 0.51 MeV band occurred when COSMOS 1176 was 2780 km from SMM. These 0.51 MeV events are discussed below.

C. HISTORY OF THE DETECTION OF NUCLEAR RADIATION FROM COSMOS 1176

During a Science Board Meeting of the Gamma Ray Experiment team in New Hampshire from October 30 to November 1, 1980, Dr. E. Rieger of Germany reported on an unusual transient in the data which he found during visual scans. Using the archival film and New Hampshire's computer, the transient was analyzed and found to be dominated by a line feature near 0.5 MeV. Some tentative screening of the microfilm produced two other sightings.

Immediately following that meeting, the NRL burst search routine, which had just been completed, was utilized to obtain a list of several more events. A list of about 10 events covering the period from 1980 April 30 to May 18 was provided to the Univ. of New Hampshire and German colleagues. Both the NRL and New Hampshire scientists noted the apparent regularity in the detected events indicating a possible association with the SMM orbit. Some speculations concerning their origin, both extraterrestrial and terrestrial were made. Following this early speculative period, a possible association of the radiation with COSMOS 1176 was realized and NRL personnel discontinued discussion of the possible origin with their collaborators in New Hampshire and Germany. Evidence for this association is presented below. From that time on both the New Hampshire and German collaborators were told that the phenomenon was not likely to be celestial in nature and

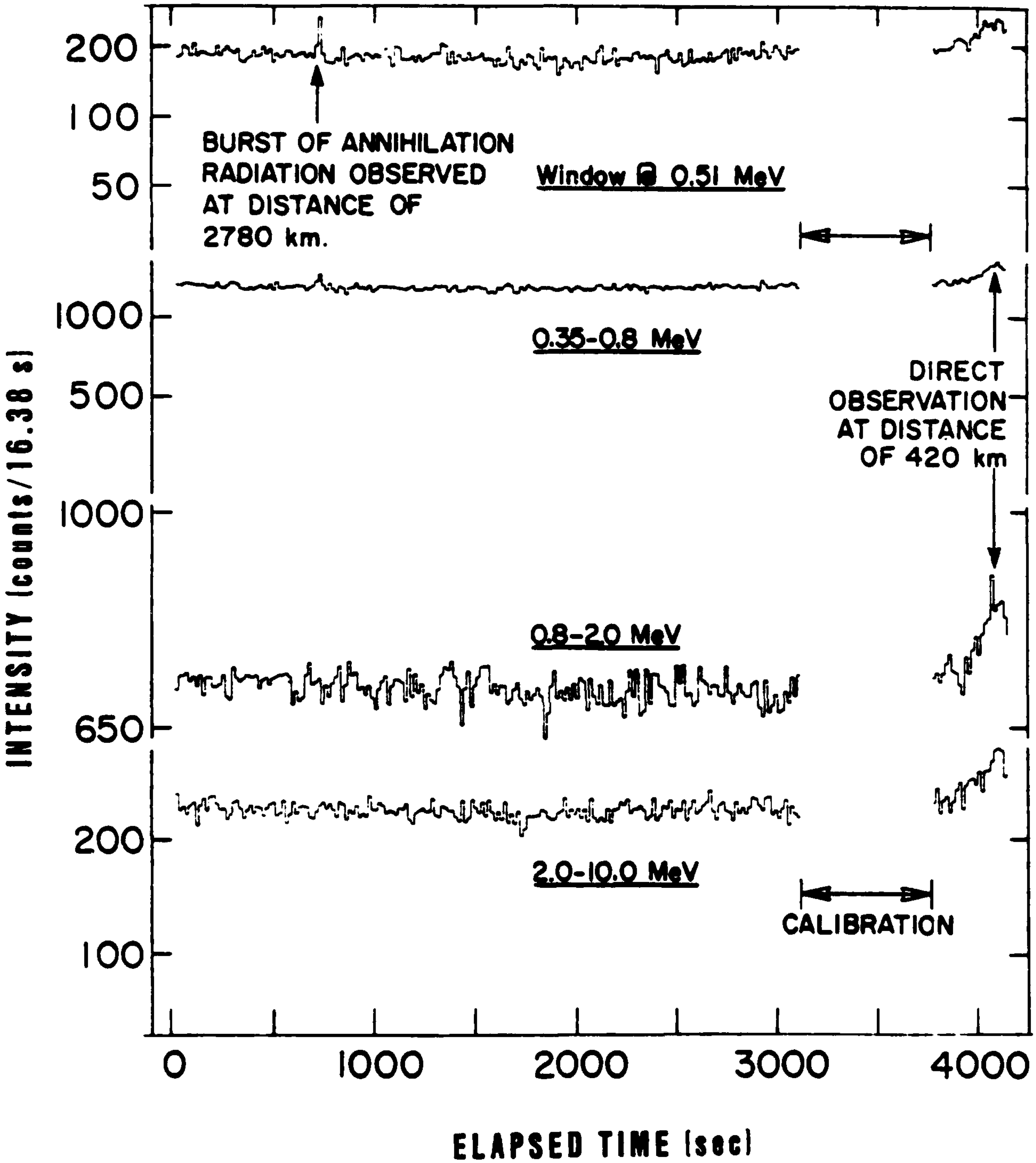

Fig. 3 — Rates observed in broad gamma-ray energy bands during an orbit of SMM on 8 May 1980 beginning at 14^h50^m U.T. Shown are detections of both a burst of annihilation radiation and nuclear radiation from COSMOS 1176 during a close approach of the two spacecraft.

that its possible origin could not be discussed. Work on these events continued at the Univ. of New Hampshire as they are in certain cases indistinguishable from cosmic and solar events. A detailed briefing of this work was presented by E.L. Chupp and D.J. Forrest at NASA Headquarters in December. The Principal Investigator, Prof. E.L. Chupp, received a briefing on portions of this report on 17 April 1981 after he obtained a secret clearance. Mr. J. Shaw, the Technical Coordinator in NASA's Office of Special Activities, DOD Affairs Division, also attended.

III. OBSERVATIONS

A. ANNIHILATION RADIATION FEATURE

1. CORRELATIONS

A computerized search for transient events in a band between 480 and 540 keV was made using the gamma ray data base covering 18 February 1980 to 10 December 1980. A list containing 26 events was obtained after eliminating spurious events caused by telemetry problems. The list was analyzed in order to find possible patterns or correlations which would lead to the origin of the events. We earlier mentioned a correlation with the orbital period of SMM. Another strong correlation that was noted was that almost all of the events occurred when SMM was near the Earth's geomagnetic equator (i.e. magnetic rigidities >12 GV). This correlation could not be produced from a random selection of sightings.

Attempts at correlating the data with geographic and celestial coodinates proved inconclusive.

The most compelling correlation is the grouping of the detected 0.51 MeV events in time. The search was performed over about one year and yet the 0.51 MeV events only occurred between April 30 and September 6, 1980. This is illustrated in the bottom part of Fig. 4. Twenty-six sightings occurred during a time interval of 130 days while none were observed in the 220 days outside this interval.

This was the first indication that the events were associated with COSMOS 1176. COSMOS 1176 was launched on April 29, 1980, and operated at its nominal 260 km orbit from that time until September 10 when the reactor was detached from the remaining part of the satellite and was boosted into a higher orbit for storage. The distribution of charged particle events shown in the top part of the figure will be discussed later in this section.

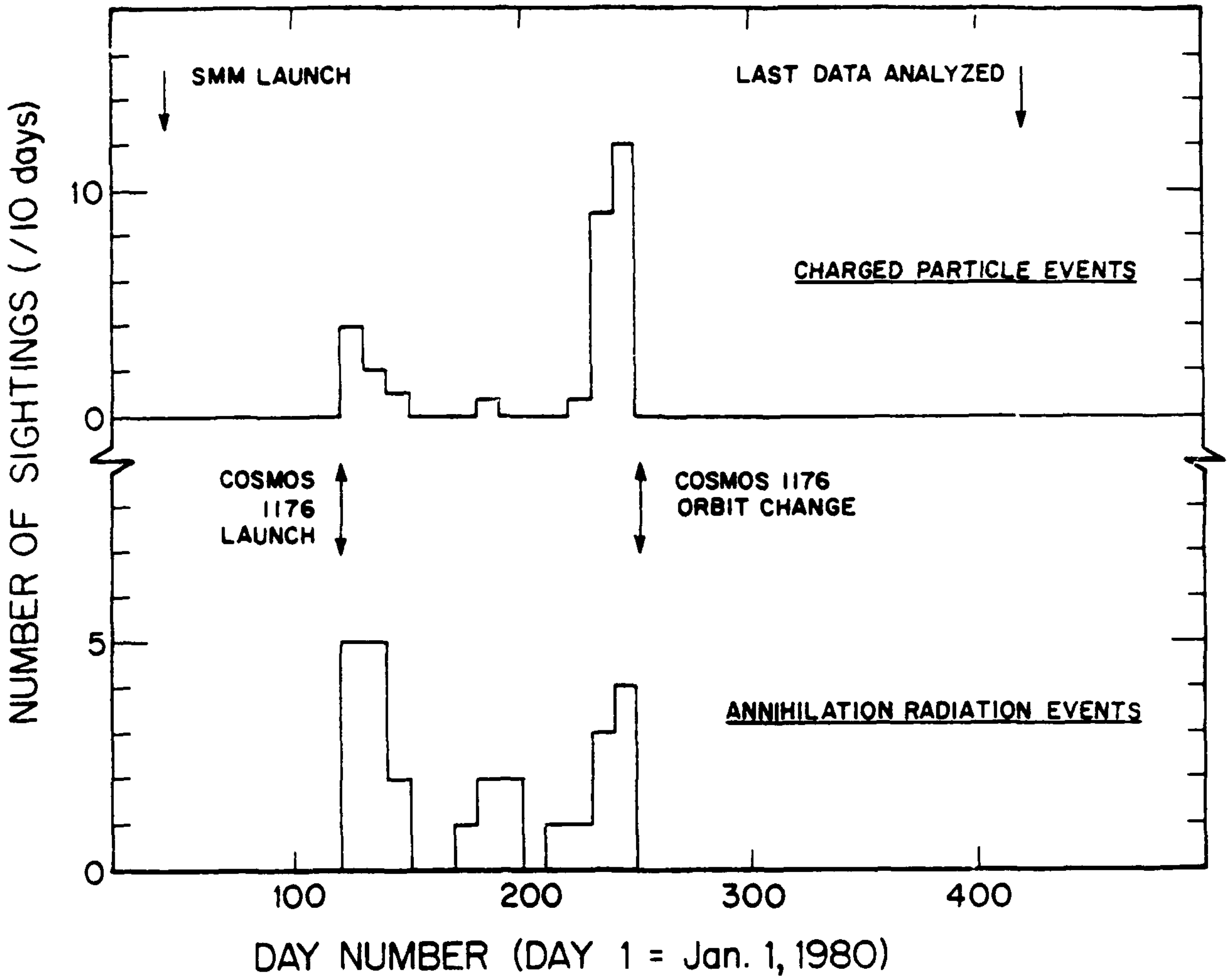

Fig. 4 — Distributions of annihilation-radiation and charged-particle events detected using a computer algorithm plotted as a function of time. The association with COSMOS 1176 is indicated.

Following up on this possible correlation with the operational lifetime of COSMOS 1176, we next investigated the frequency that COSMOS 1176 was within the line of sight of SMM (<4500 km) when the events were detected. In order to obtain a comparison, we also did the same study using 63 other satellites having similar orbits to that of COSMOS 1176. In this early study only 24 of the 0.51 MeV sightings were used. In 17 of these 24 sightings COSMOS 1176 was within 4400 km of SMM. The next highest number of possible correlations was 11 for a Soviet meteorological satellite. Most sightings for random satellites were less than six. The correlation with COSMOS 1176 is unlikely to be due to a statistical fluctuation. Using the full sample of 26 events and improving some of the orbit calculations, we found that COSMOS 1176 was within 5500 km of SMM in 22 out of the 26 sightings.

It is also of interest to investigate the distribution in distance with respect to the intensity of the observed 0.51 MeV radiation. This is done in Fig. 5 in which data from 19 of the 26 sightings are plotted. There is no apparent correlation in the observed intensity with the distance of SMM from COSMOS 1176. The intensities plotted range between 30 and 300 counts and measure the peak number of counts observed above background in a 16.38 s accumulation period at the peak of the emission.

Durations of the observed 0.51 MeV emission are generally shorter than 100 sec. Shown in Fig. 6 are the time histories of four events. In each plot, the top trace gives the 16.38 sec accumulations in a window near the 511 keV annihilation line. The middle trace contains data from a 50 keV band around 300 keV. It is plotted at a resolution of 2 sec and measures Compton continuum photons from the annihilation feature. The bottom trace plots charged particle intensities observed in the plastic scintillation counters above and below the detector. The durations of these representative events varies from <2 sec to >120 sec. There is evidence for the detection of charged particles during two of these events, however, their time profiles appear to be shifted in time from the 511 keV emission.

We find evidence for weak charged particle fluxes in about two-thirds of the 511 keV events studied. However, the temporal structure of the 511 keV and charged particle emissions are not always identical (see Sec. IV F).

2. DETAILED SPECTRA OF 511 keV ANNIHILATION RADIATION

Up to this point we have based most of our discussion on the rates observed in a window near 0.51 MeV. In this section we discuss the detailed spectral measurements of these

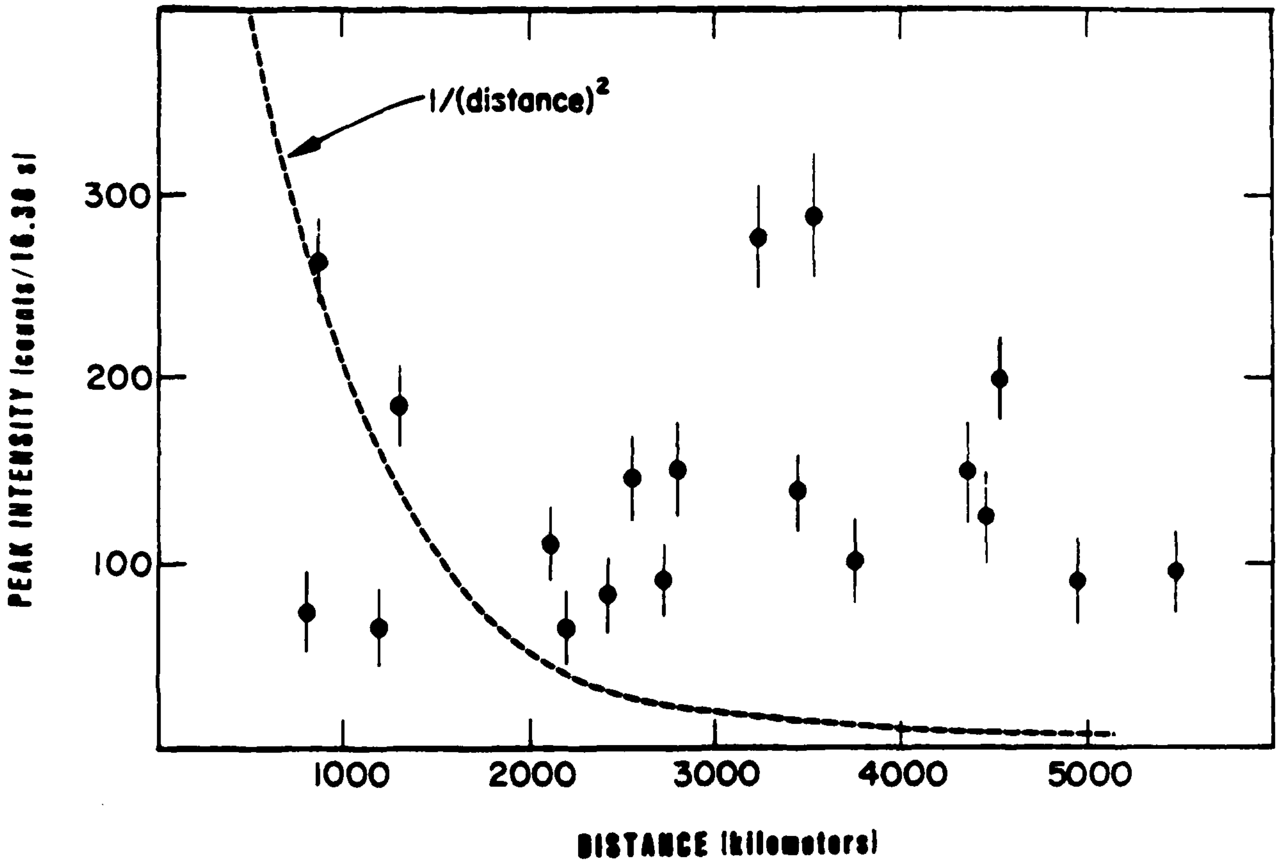

Fig. 5 — Peak intensities (16.38s integration) of annihilation radiation events plotted as a function of distance between SMM and COSMOS 1176. For comparison, the dashed curve exhibits the expected distribution for a source emitting radiation isotropically.

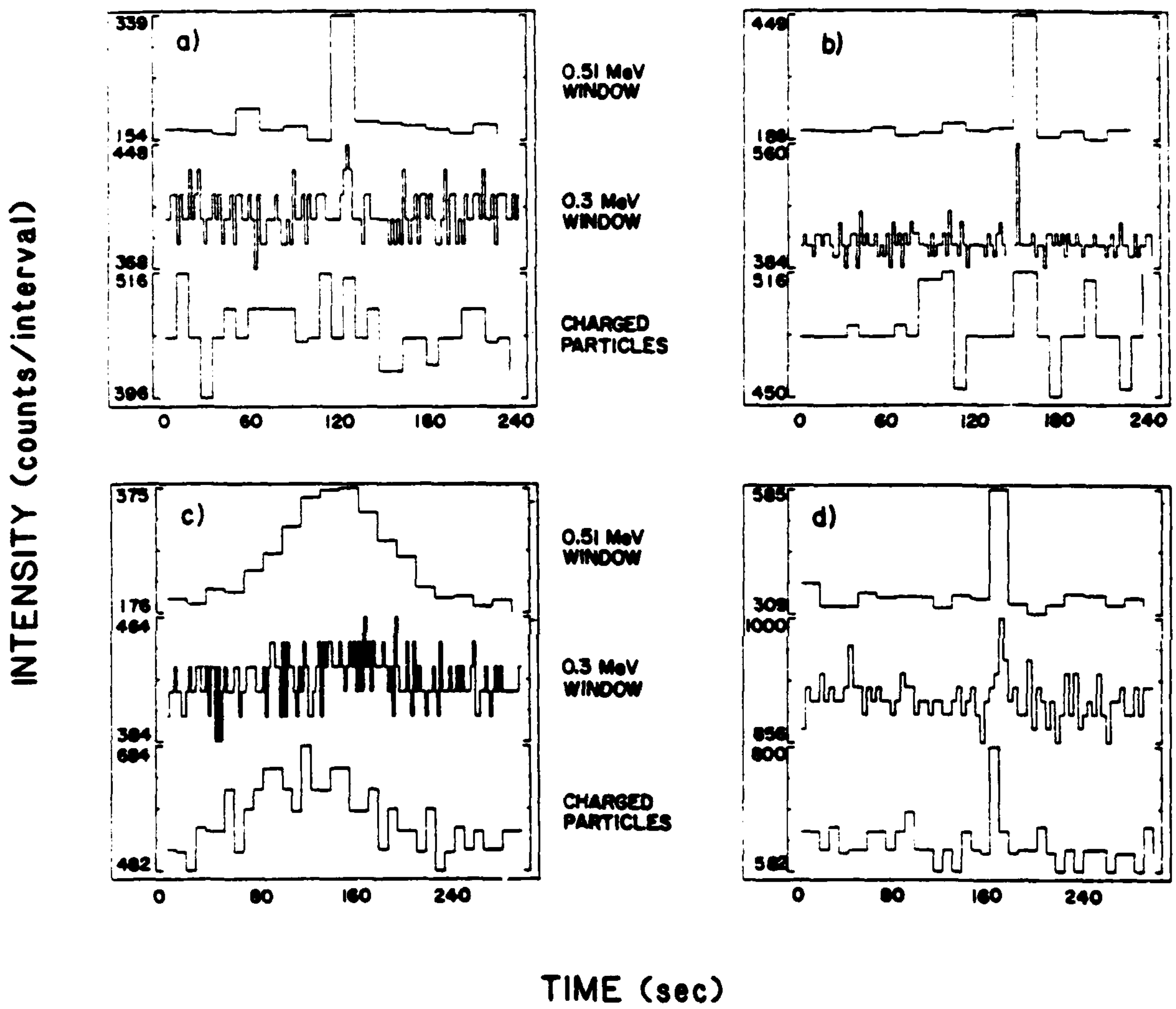

Fig. 6 — Time profiles of four bursts of annihilation radiation as observed in three data channels. The 0.51 MeV channel is derived from 16.38s spectral accumulations, the 0.3 MeV window rates (cts/s) come from a separate high time resolution channel of the instrument, and the charged particle rates (sampled for 0.5 s every 8 s) come from the plastic scintillation detectors.

events. The spectrum from one such event is shown in Fig. 7 after correcting for background. This event occurred on May 12, 1980, when SMM and COSMOS 1176 were about 4600 km from one another. It had one of the longest durations observed, 150 s (see Fig. 6c). This spectrum and all others of this type are dominated by a single line feature near 500 keV.

The data channels at higher energies have been summed in order to search for any high-energy continuum emission. None was observed; all of the measurements at energies above the line feature are consistent with upper limits. The spectrum at lower energy can be explained by Compton degradation of the incident radiation prior to being detected and by the Compton tail in the detector. The observed photopeak to Compton ratio is 5:1; one would expect a ratio of 7:1 based on calibrations. It is therefore likely that the incident beam suffered some scattering prior to detection by the spectrometer.

Gamma rays of 511 keV energy have been detected during a solar flare on 21 June 1980 and after irradiation by the particles in the South Atlantic Anomaly. The peaks in the spectrum attributed to COSMOS 1176 are within the experimental error ($\pm$ 3 keV) of these well established peaks at 511 keV. This identifies the feature conclusively as the positron-electron annihilation line.

The measured width of the line is approximately 34 keV. This is about 6 keV broader than we estimate the instrumental resolution to be at this energy. It is difficult to assess at present whether this increased width is significant.

We have studied the spectra of 25 of the events in detail. Each of them exhibit a line feature at about 511 keV and approximately the same width. In two instances the measured widths are somewhat larger, but this may be statistical in nature.

It is also of interest to note that four events detected when COSMOS 1176 was more distant than 6400 km from SMM all show the same characteristic spectra.

B. CHARGED PARTICLE DETECTIONS

As we noted in the previous section, charged particles were weakly detected in more than half of the 511 keV events. This led us to investigate whether we might detect stronger charged particle events that might be associated with COSMOS 1176. In order to do this we utilized the same computer algorithm for detecting the 511 keV events, but instead applied it to the counting rates observed in the plastic scintillation detectors (see Fig. 1). These detectors

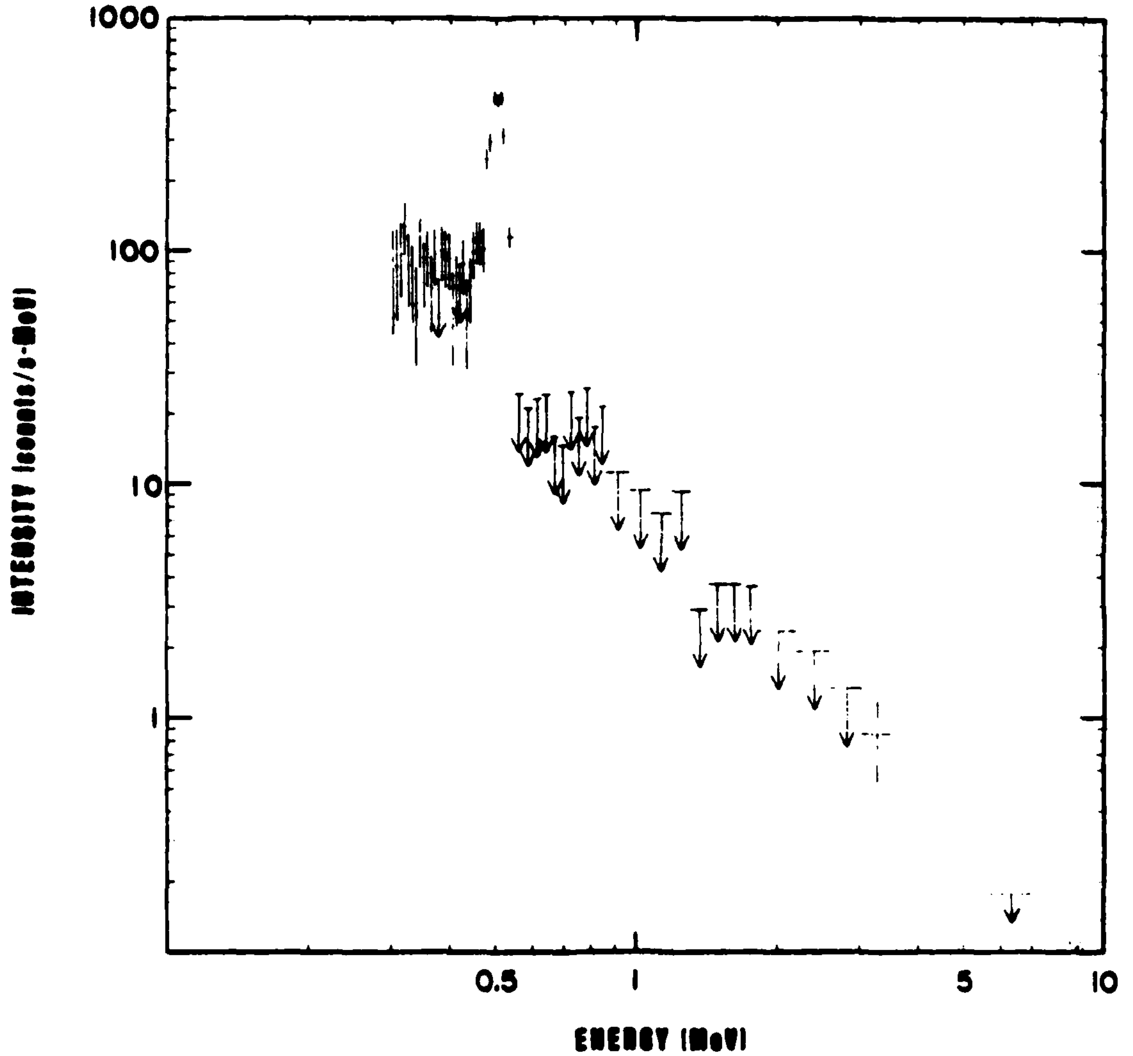

Fig. 7 — Energy loss spectrum of the annihilation event on May 12 corrected for background but not corrected for instrument response. Channels >520 keV have been summed to improve statistics.

are sensitive to particles with energies above a few hundred keV.

The search was performed over the operational life time of COSMOS 1176. Shown in the top portion of Fig. 4 is the frequency of detections of otherwise unexplained charged particle events. This distribution is similar to that observed for the 511 keV events. Note, however, that we have not fully investigated the SMM data base outside the time interval including the COSMOS 1176 operational period. There is no evidence to believe that charged particle events of this nature occurred outside that interval, however.

Shown in Fig. 8 are time histories of two of these charged particle events which reflect the range of events detected. The rates were sampled for 0.5 sec every 8 sec. The durations of the charged particle events ranged between <8 sec and ~100 sec. In most instances these particles were also detected by the Hard X-Ray Burst spectrometer on SMM. These events were observed in data from that experiment provided by NASA on our telemetry tapes. The responsible investigator (Mr. K. Frost, NASA-Goddard Spaceflight Center) is not aware of these observations.

C. DIRECT OBSERVATION OF COSMOS 1176

As we noted in discussing the orbital data shown in Fig. 3 the SMM instrument detected a noticeable increase in the 350 keV to 10 MeV energy range during a passage within 340 km of COSMOS 1176. This occurred during the night-time portion of the SMM orbit when COSMOS 1176 was well within the field of view of the gamma-ray detector. Detailed spectra of the gamma radiation accumulated over 165 s during this period of close approach of COSMOS to SMM is shown in part a) of Figs. 9 and 10. The spectra have been corrected for background but have not been corrected for instrument response. Data below about 550 keV have been plotted in Fig. 9 a) at the full spectral resolution of the instrument. At higher energies, channels have been summed in order to provide statistically significant data for exhibiting the general features of the emission.

The spectrum plotted in Fig. 9a has clear features that may be due to individual lines or combinations of lines unresolved by the SMM detector. We have attempted to fit some of the features observed below 1 MeV and these results are summarized in Table 1. Caution must be taken in interpreting these results because of an uncertain absolute energy calibration at energies below ~400 keV.

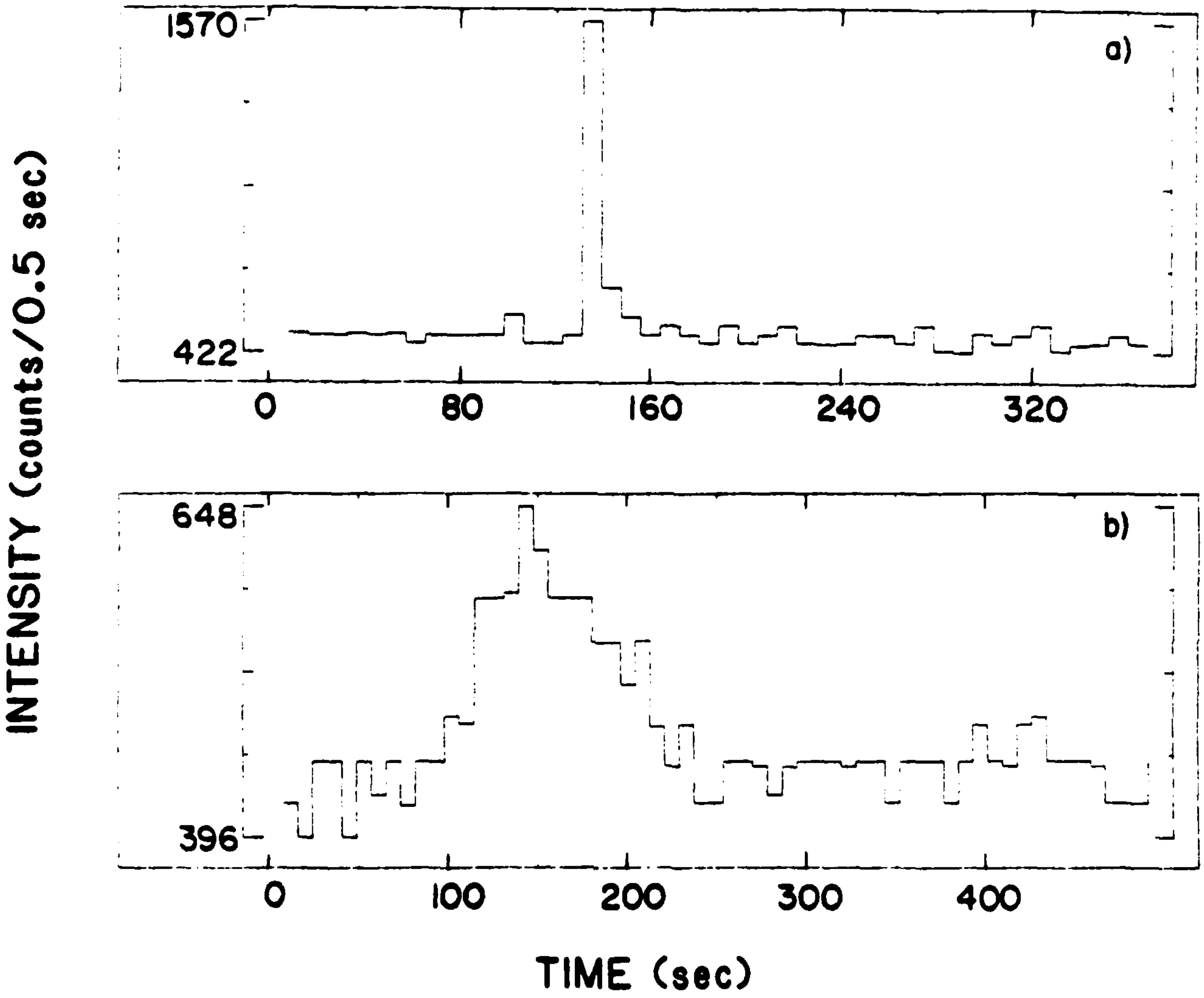

Fig. 8 — Time profiles of two charged particle events detected by the plastic scintillation detectors. The rates are sampled for 0.5 s every 8 s.

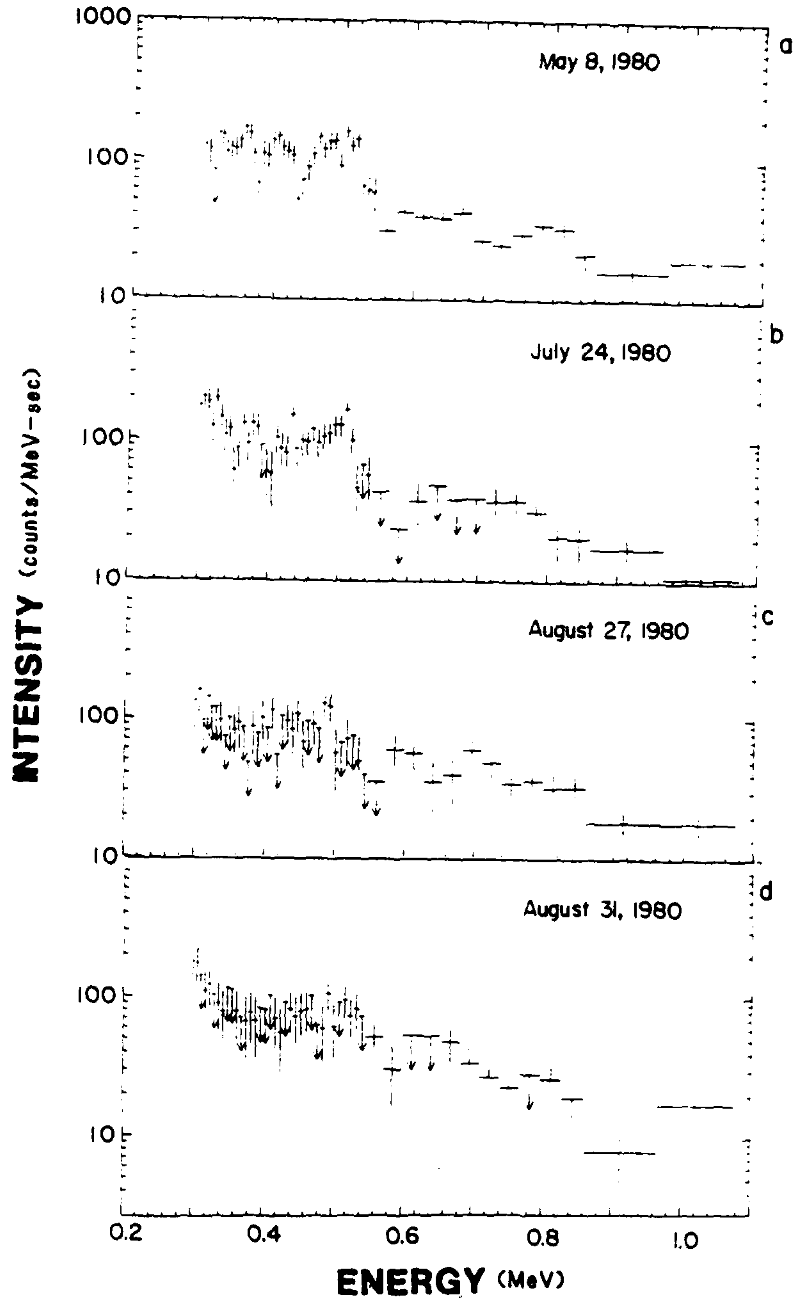

Fig. 9 — Gamma-ray spectra between 0.3 and 1.0 MeV obtained during four close encounters of COSMOS 1176 with SMM. The spectra have been corrected for background but not corrected for instrument response.

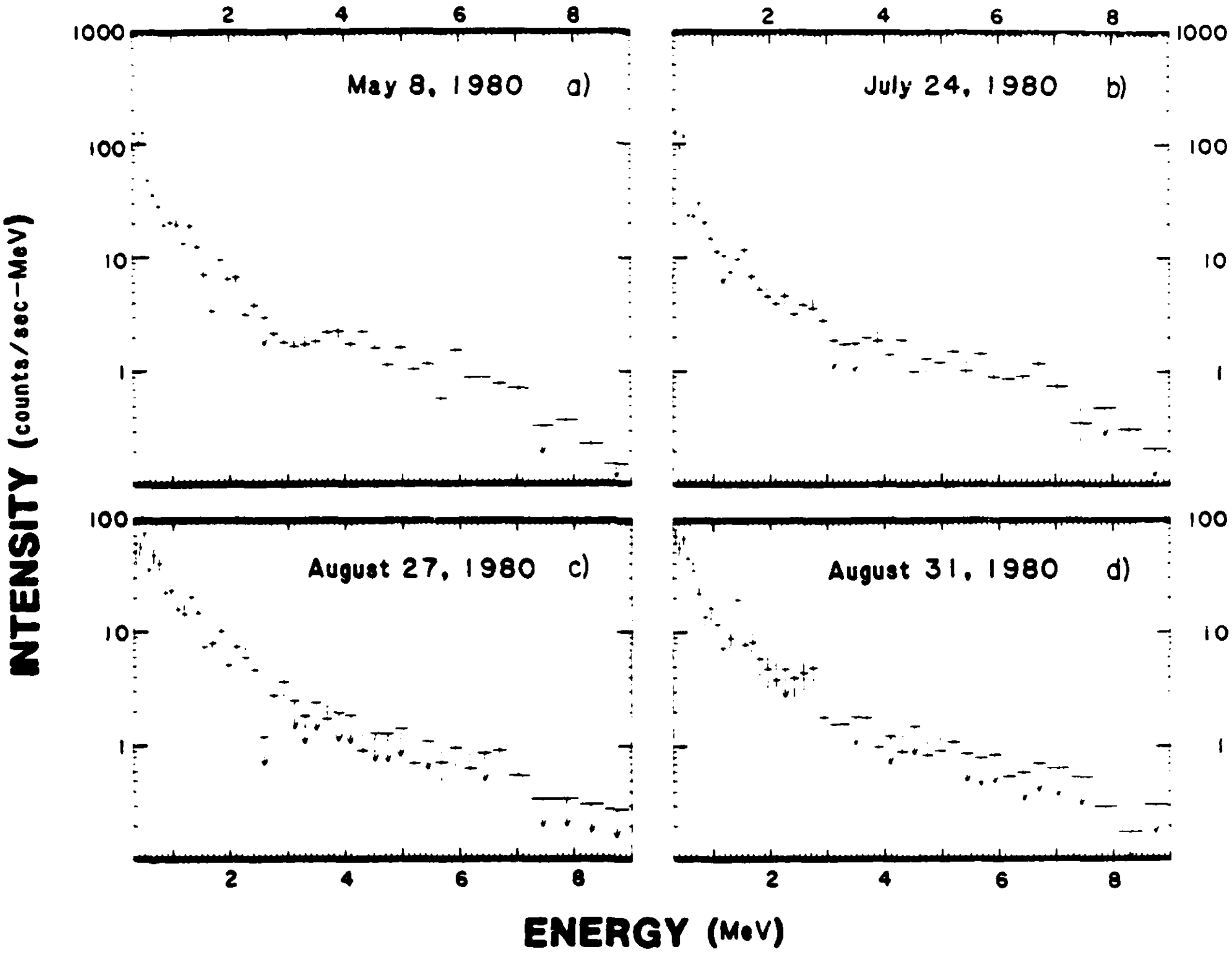

Fig. 10 — Gamma-ray spectra between 0.3 and 9.0 MeV obtained during four close encounters of COSMOS 1176 with SMM. The spectra have been corrected for background but not corrected for instrument response.

Table 1

Fits to Features in the Gamma-Ray

Spectrum from COSMOS 1176

Energy (keV)		Measured Width (keV)	Instrumental Width (keV)
367 ± 3		12 ± 4	21
414 ± 4		22 ± 4	22
499 ± 5	(single line fit)	52 ± 13	27
479 ± 6	(2 lines fit)	29 ± 9	27
517 ± 5		24	27
803 ± 7		40 ± 13	39

A single line fit to the data near 500 keV yields a width too large relative to the instrument's resolution. Therefore, we have fit the data using two lines in the region. Both sets of fits are given in the table. The feature at 367 keV is somewhat narrow to be a line but this could be due to limited statistics. Interpretations of these line features are given in Section IV.

Also plotted in Figs. 9 and 10 are the background corrected spectra obtained during three other occassions when COSMOS 1176 passed within the field of view of the SMM γ-ray detector at distances <400 km. We have not attempted to normalize the data relative to the average distances of the observations; therefore, comparison of relative intensities using these figures is not meaningful. What is important is a comparison of the general spectral features. In Fig. 10 we note that all four exhibit a similar spectral shape, being relatively steep below ~1 MeV and flat from 2 MeV to ~7 MeV. All exhibit a decrease above ~7 MeV.

Changes are evident in Fig. 9 at energies below 600 keV. Features that were significant during the May 8 encounter are much less striking on July 24 and hardly visible in the latter part of August.

IV. ANALYSIS AN^ INTERPRETATIONS OF THE DATA

A. THE HIGH-ENERGY PART OF THE GAMMA-RAY SPECTRUM OBSERVED FROM COSMOS 1176

The high-energy parts of the gamma-ray spectra shown in Fig. 10 show a nearly constant number of counts in the region 3-7 MeV and a marked reduction for the region above 7 MeV. This characteristic is seen more clearly in Fig. 11 in which the combined spectrum from the four observations shown in Fig. 10 is plotted. Statistically significant features are apparent at high-energy. The fitted energies are 6.81 MeV and 6.0 MeV with statistical uncertainties of about 50 keV. The systematic uncertainties due to instrument calibration have not been measured at this energy but are believed to be <100 keV. The general characteristics of the detector response shown in Fig. 11 can be explained by photopeak emission from one or more high-energy γ-rays plus a Compton continuum. It is puzzling that the single escape peak expected near 6.3 MeV from the 6.8 MeV line is not evident. The feature near 6.0 MeV is too low in energy to be compatible with this escape peak. These high-energy gamma rays could come from three possible sources:

a. Neutron capture in the COSMOS 1176 satellite.

b. Neutron capture in the SMM satellite, the neutrons originating in the COSMOS satellite.

c. Neutrons originating in the COSMOS 1176 satellite being captured in the iodine of the sodium iodide scintillation detector.

The RORSAT reactor on COSMOS 954 was a beryllium moderated and reflected reactor with uranium-molybdenum (~10%) fuel and sodium-potassium coolant (Bennett 1989). Neobium cladding material was probably used along with stainless steel structural material. There should be a significant amount of neutron capture occurring in the Be and Mo and possibly in Na.

The neutron capture gamma-ray spectrum of Be is dominated by a strong gamma ray at 6.81 MeV, and that of Mo by a strong gamma ray as 6.92 MeV. The high energy part of Fig. 11 could be explained by one or both of these sources, but not by any one of a number of other materials, such as aluminum, niobium, magnesium, iron, chromium, nickel, sodium, calcium, hydrocarbons, or plastics. The observed count rate

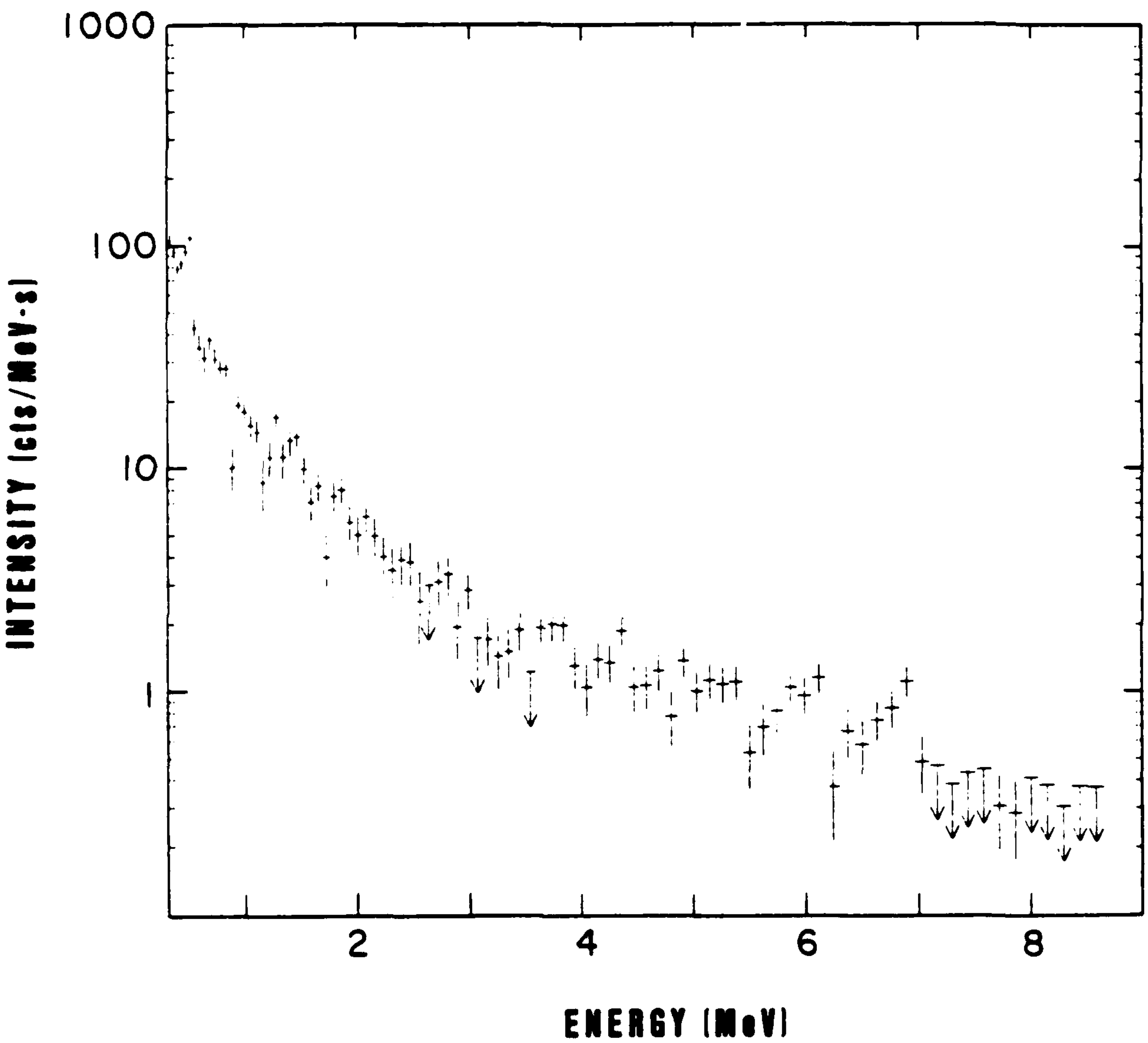

Fig. 11 — Summation of the four spectra plotted in Fig. 10 corrected for background but not for instrument response.

in the high energy domain is roughly consistent with what one would expect from a bare reactor operating at 10-100 kW at a distance of 340 km.

Neutron capture in the iodine of the detector has been observed in the laboratory to produce a spectrum with a similar shape and energy cut-off as those shown in Figs. 10 & 11. If one assumes that the reactor power is in the range of 10-100 kW, and is located at a distance of 340 km, the detector count rate due to neutron capture in iodine would be a few counts per second. The observed count rate is consistent with this calculation.

Pending more spectral analysis, it is not possible to determine with any certainty the origin of the 6.8 MeV gamma-ray feature in the spectrum. The best possibilities based on our current knowledge, however, are neutron capture in beryllium (possibly also in molybdenum) in the COSMOS 1176 nuclear reactor. Alternatively, neutrons from the COSMOS 1176 captured in the iodine of the detectors on board the SMM can also produce similar spectral features.

B. THE LOW-ENERGY PART OF THE GAMMA-RAY SPECTRUM OBSERVED FROM COSMOS 1176

The low-energy spectrum of the May 8 sighting in Fig. 9 has been analyzed in a simple way to give the results in Table 1. Until the detector response functions are developed, no further analysis is likely to produce unambiguous results. As discussed above, the low-energy gamma rays could be produced by neutron capture in either of the satellites. Although no definitive conclusions have been reached, the following possible line identifications are suggested: 367 keV, neutron capture in iron (Fiebiger et al. 1962); 479 keV, from sodium or boron; 517 keV, positron annihilation; 803 keV, molybdenum (Rasmussen et al. 1967). Further speculation appears unwarranted until a more complete analysis of the spectrum can be made.

C. REACTOR POWER

It would be desirable to determine the power of the nuclear reactor on board the COSMOS 1176 satellite. One method of obtaining the power is by comparing the observed emission with that from a reactor of known power. A γ-ray spectrum from a Bulk Shielding Reactor (BSR) (Maienshein and Love, 1954; Goldstein, 1959) is available; however the reactor is light-water moderated and contains aluminum structural materials. It is therefore not surprising that the spectrum is different from the one observed from COSMOS 1176. Whereas, the differential intensity from COSMOS is relatively constant in the 3 to 6 MeV range, the intensity from the BSR decreases

by an order of magnitude in going from 3 MeV to 6 MeV. Furthermore, the high energy fall off from the BSR occurs above ~7.7 MeV, which reflects the fact that this reactor contains a significant amount of aluminum. It is also possible that the spectrum detected by SMM is not due to γ-rays from COSMOS, but from γ-rays produced in SMM by neutrons emitted by COSMOS. Therefore, many assumptions would need to be made in order to use the BSR to obtain the power of the COSMOS 1176 reactor.

Another significant uncertainty is the amount of shielding covering the reactor. This amount of shielding depends upon reactor design and also varies with the viewing angle. Evidence is seen for such shielding effects when data from the four close approach sitings are analyzed in detail. However, the results from one observation to another are not totally consistent, which may indicate movement of material in COSMOS 1176. Further work is needed in this area.

It appears that information on the variation of reactor power over COSMOS' lifetime will be forthcoming from the SMM observations. However, the uncertain amount of shielding material and lack of knowledge of reactor design will limit the accuracy of any estimates of the absolute power of the reactor.

D. SPECTRAL VARIABILITY

Although the absolute power is difficult to estimate, something can be said about variability in power and spectral shape during the mission of COSMOS 1176. The best evidence for variability is provided in Figure 9. As noted earlier, spectral features which are prominent on May 8 are missing by the end of August. The relative trajectories of SMM and COSMOS 1176 are similar during their close approaches on May 8 and August 27 with the exception that their relative directions of motion are reversed. Therefore, unless COSMOS 1176 was in a different orientation relative to its direction of motion on the two days, these two exposures should be similar. The fact they are not indicates that some basic change has taken place. Because the spectral features appear below 600 keV leads to the conclusion that their source must be near the outside shell of COSMOS 1176. Because propellant is used during the mission, one might expect that a possible source for the spectral features are γ-ray lines emitted by propellant irradiated by neutrons. All known or suspected propellants, however, contain significant amounts of hydrogen. Neutron cpature on hydrogen results in a distinctive 2.2 MeV γ-ray which has not been observed. Further spectral analysis and comparison with characteristics of alternative propellants is necessary to investigate this effect. Another possible explanation for the change in spectral

features are changes in the reactor's shield, reflector or coolant during its lifetime.

The overall intensity in the high-energy region of the spectrum appears to have decreased to about 50-70% of its initial value by the end of August. This is based on a comparison of the total rates observed in the 2-10 MeV range on May 8 and August 27 during the one minute of close approach when the distances and viewing angles were similar. Whether this change reflects a decrease in the power of the reactor or some change in the material surrounding it cannot be determined at present.

E. ORIGIN OF BURSTS OF ANNIHILATION RADIATION

The overwhelming correlation with the operational period of COSMOS 1176 and its position relative to SMM leads to the conclusion that the bursts of radiation at 511 keV are associated with COSMOS. Most of the observations to date can be explained by the motion of charged particles in the earth's magnetic field.

The basic postulates are: (1) the positrons originate in the shell of COSMOS 1176 via electron-positron pair production arising from the intense gamma-ray flux with energy greater than 1022 keV; (2) the positrons reach SMM by moving in helical paths along the earth's magnetic field lines; (3) the positrons annihilate in the satellite and detector materials of SMM. Fig. 12 schematically depicts this model which explains most of the phenomena observed. A large amount of information exists on the earth's trapped radiation (Hess and Mead 1968; Cladis et al. 1977). We also note that Hones (1964) earlier suggested the use of positrons as a means of studying the Earth's magnetic field. We list below the supporting arguments for this explanation.

1. Intensity Estimate

In order to calculate the effective source of positrons from COSMOS 1176 the following assumptions were made: (1) the reactor is essentially unshielded and operating at 50 kW thermal power; (2) the gamma-ray spectrum is that of the Bulk Shielding Reactor (as discussed earlier this is only an approximation); (3) the outer skin of the COSMOS 1176 satellite is aluminum, (4) an effective area of only 10^3 cm^2 was irradiated with the reactor gamma rays. One calculates then that approximately $2x10^{12}$ positrons per second are emitted. Although additional attenuating material would reduce this number, there are a number of effects which would tend to increase it: (a) the effective "radiating area" is probably much larger than 10^3 cm^2, (b) the interaction cross section for higher atomic number materials would give a larger number of

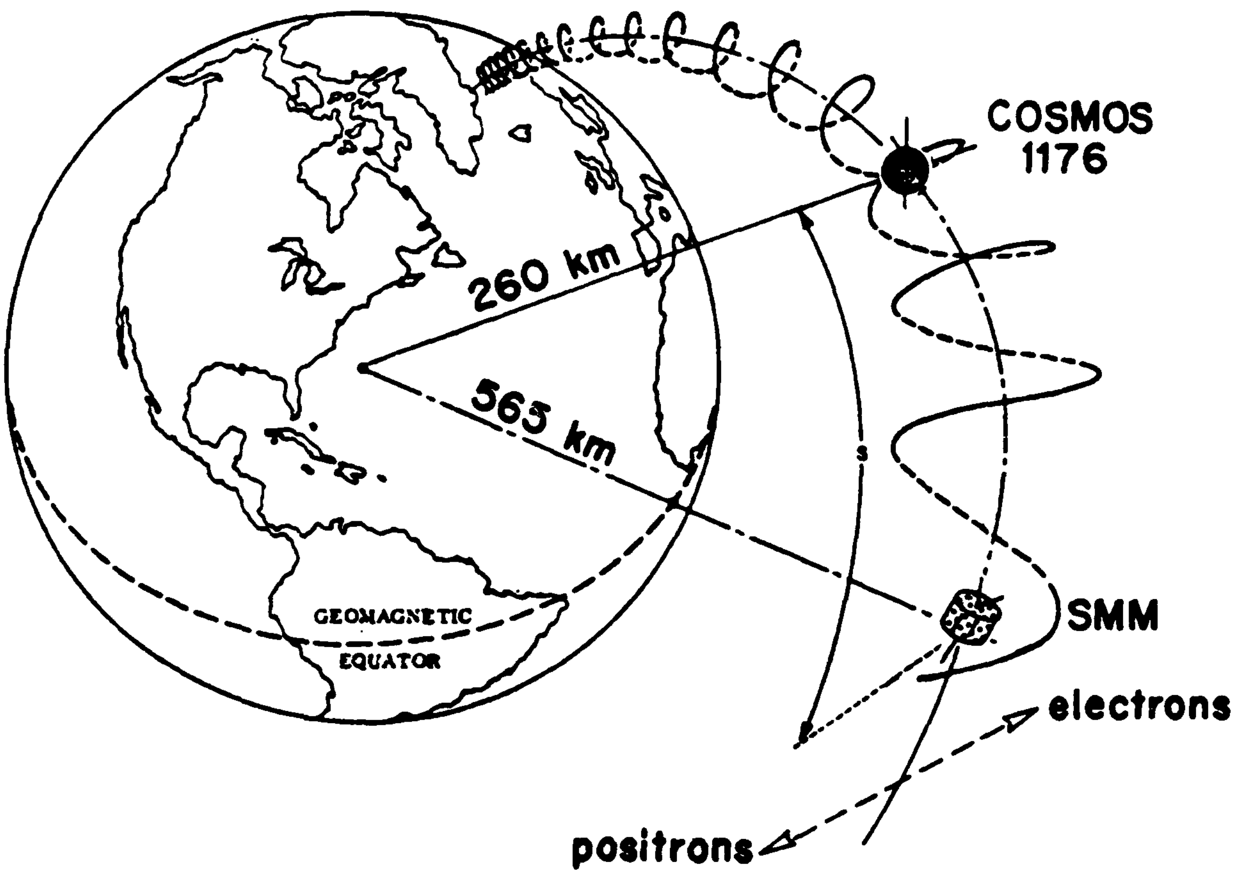

Fig. 12 — Illustration of model explaining annihilation and charged particle events associated with COSMOS 1176. Electrons and positrons emitted from COSMOS reach SMM by travelling along the earth's magnetic field lines. Electrons and positrons drift in opposite directions as shown.

positrons, (c) the observed spectrum for the COSMOS 1176 reactor appears to contain a much higher proportion of high-energy gamma rays than for the BSR.

The positrons travel in helical paths along the geomagnetic field lines with sufficient velocity that they travel from pole-to-pole in approximately 0.1 second. Since we have observed the "gamma-bursts" to last from a few seconds to a few minutes, it appears that the paths of the two satellites are intersecting the same geomagnetic lines for times of that order. In that event, the SMM satellite would be struck with approximately 2×10^{12} positrons per second. On the other hand, the positrons are emitted at various angles and energies such that they have a large variation in velocity along the field line. After a few reflections by the converging magnetic field lines the positrons are nearly uniformly distributed along the field lines. In one second, the distributions of positrons along the field lines would be approximately 10^5 positrons/meter. If the SMM intersects a one-meter wide section of these "filled" field lines for one second, there would be 10^5 positrons annihilating on the SMM during that one-second "gamma-burst." The efficiency of the SMM gamma-ray spectrometer to detect positrons is expected to be of the order of 10^{-2} to 10^{-3}, therefore producing a counting rate in the 511-keV peak of the gamma-ray spectrum of approximately 100 to 1000 counts/sec. In fact, the observed count rate is lower, approximately 10 counts/second, which therefore allows for the losses when positrons enter the atmosphere at their reflection points.

2. Lack of Correlation with Distance.

The intensity has been observed to be independent of the distance between satelites. This is consistent with charged particles filling a magnetic flux tube.

3. Temporal Distribution

The distribution in duration of the events can be explained by the motion of SMM relative to the field lines connecting it to COSMOS 1176. The full explanation of the two long duration events ($\gtrsim$3 min) is not known at present, but is under investigation.

4. Over the Horizon Detections

The field line model explains the bursts which have originated from COSMOS 1176 when it is over the earth's horizon from SMM.

5. Correlation with the Geomagnetic Equator.

(S) The field line model readily explains why most of the detections of 511 keV bursts occur when SMM is near the geomagnetic equator (i.e. at high geomagnetic rigidities). This is true because field lines reach their greatest distance from earth at the equator giving positrons created at 260 km altitude the opportunity to "ride" to the 560 km altitude of SMM (see Fig. 12).

6. Agreement with Field Line Tracing of 511 keV Events

A study has been made of motion of charged particles in the geomagnetic field near COSMOS 1176 and SMM when the 511 keV events were detected. Four cases are shown in Fig. 13. The positions and directions of motion of both satellites are shown. Also noted is the position of the field line at the altitude of COSMOS 1176 which crosses SMM. These field line tracings have been done using a program furnished us by Dr. D. Smart of the Air Force Geophysics Laboratory and have been confirmed by independent calculations done by Dr. D. Sawyer at Goddard. In all but two cases, the field line lies close to and to the west of COSMOS 1176. This westward drift is consistent with that expected for positrons in the Earth's magnetic field (see Fig. 12).

The long duration event of May 12 (see Fig. 6c and Fig. 7) and a similar one observed a day later do not appear to agree with the simple model. The geometry for the May 12 event is shown in the lower right of Fig. 13. Further work is being done to understand these events.

F. ORIGIN OF THE CHARGED PARTICLE EVENTS

The charged particle events discussed earlier are explained by the same model. These charged particles are in fact electrons produced by both pair production and Compton interactions of the reactor γ-rays in the structure of COSMOS 1176. The intensity of these electron events are about an order of mangitude higher than the positron events. This is in agreement with estimates of the relative rates of production of positrons and electrons. However, the electrons are more difficult to detect than the positrons which appear in the narrow 511 keV line feature.

Shown in Fig. 14 are four electron events which confirm the magnetic field hypothesis. In this case the position of the field lines at 260 km which cross SMM are to the east of COSMOS 1176. This is consistent with the expected eastward drift of the electrons (see Fig. 12). All of the electron events detected are consistent with the model.

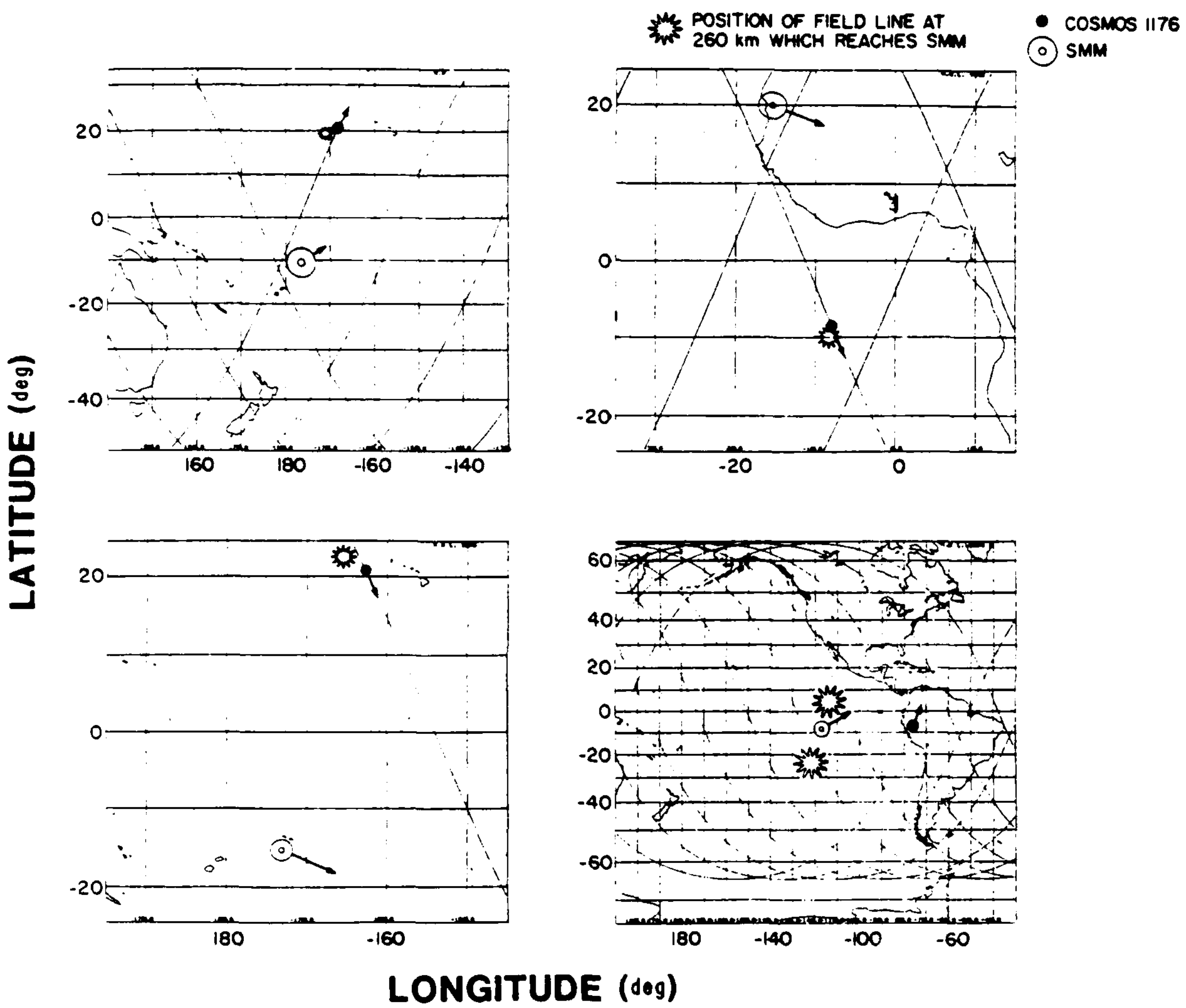

Fig. 13 — Maps depicting the positions of SMM and COSMOS 1176 at the times of four of the annihilation radiation events. Also shown is the location of the magnetic field which crosses SMM at the altitude of COSMOS 1176.

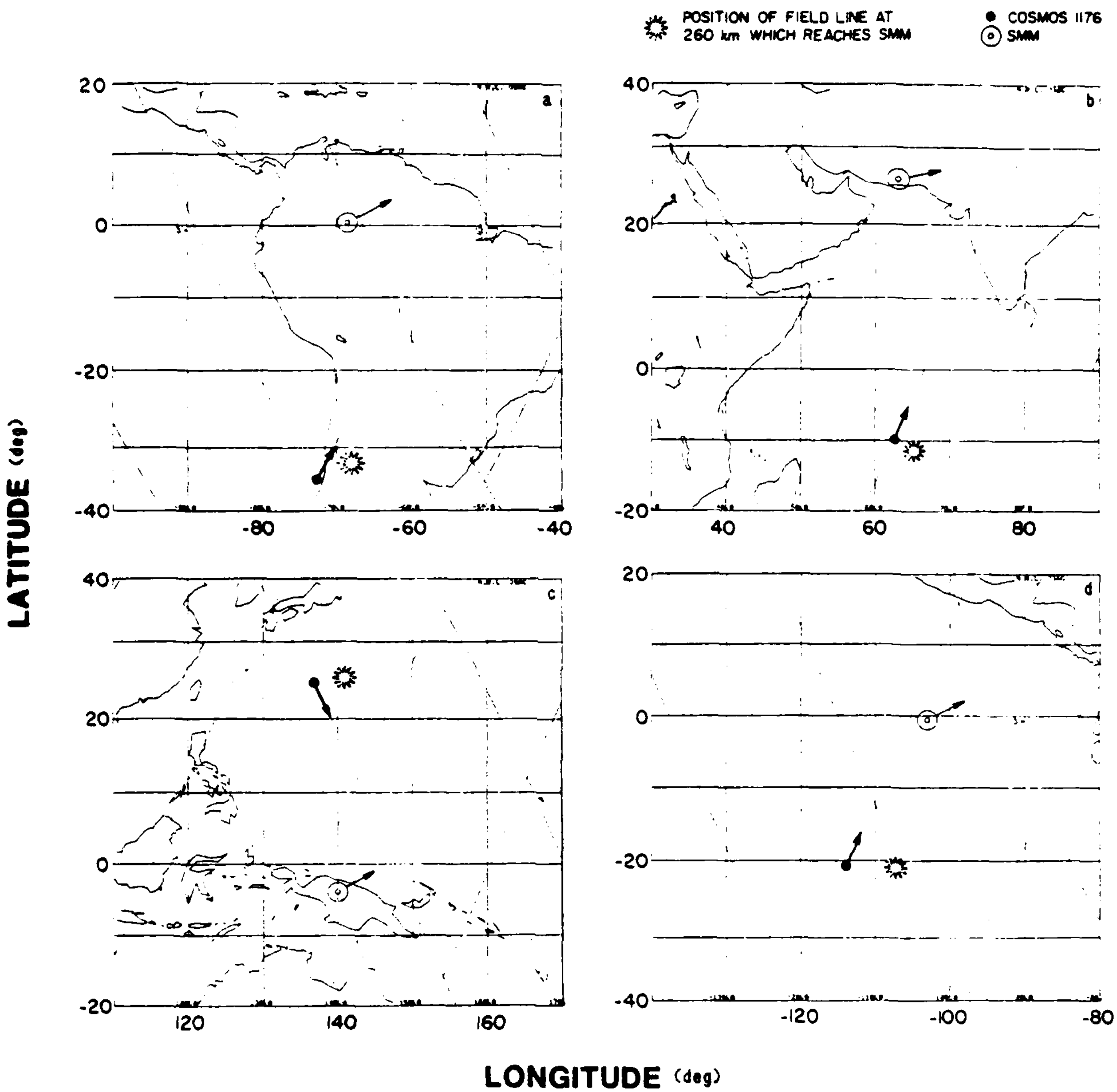

Fig. 14 — Maps depicting the positions of SMM and COSMOS 1176 at the times of four of the charged particle events. Also shown is the location of the magnetic field which crosses SMM at the altitude of COSMOS 1176.

G. SEARCH FOR NUCLEAR RADIATION FROM COSMOS 1176 IN ITS HIGHER ORBIT

A search has been conducted for nuclear radiation emitted by COSMOS 1176 after it was boosted into its higher orbit (926 km) in early September. Utilizing ephemeris information, the SMM archival plots were inspected for enhanced γ-ray emission when COSMOS 1176 was within 550 km. Fifteen such close approaches were analyzed over the time period from 12 September 1980 until 7 December 1980. No detectable nuclear radiation was observed.

We conclude from this study that the flux of nuclear radiation emitted by COSMOS 1176 in its higher orbit at the time of these observations was at least an order of magnitude below the flux emitted in the early part of May 1980. Due to the limited number of observations we cannot exclude the possiblity that the reactor has been reactivated while COSMOS 1176 has been in its higher orbit.

H. NARROW SPIKES DURING CLOSE APPROACH SIGHTINGS OF COSMOS 1176

During some of the close approach sightings of COSMOS 1176, within distances of 550 km, relatively narrow spikes of charged particles and low energy γ-rays have been detected. These phenomena have not been investigated in detail. Some of these spikes occurred with COSMOS 1176 180° from the forward aperture of the γ-ray detector. Variations in absorption due to shielding material between SMM and COSMOS is a likely explanation of these phenomena.

V. FURTHER WORK

Detailed analysis of the SMM data concerning COSMOS 1176 is continuing in collaboration with the Los Alamos Scientific Laboratory. At Los Alamos this involves staff members in the Energy Division (Critical Experiments and Diagnostics Group and the Reactor Space Power Technology Group), The Physics Division (Neutron Physics), The Space Sciences Office and The International Technology Office.

The purpose of this work is to analyze in detail both the line features of the observed γ-ray spectra and their variability, and to describe quantitatively how the trapped positron/electron theory explains the observed 0.51 MeV and charged particle events.

VI. DETECTION AND ANALYSIS OF OTHER SOVIET NUCLEAR SPACECRAFT

Aviation Week reported that COSMOS 1249, launched on 5 March 1981, had characteristic of previous spacecraft containing nuclear reactors. Preliminary work at NRL on the current SMM data base indicates that nuclear radiation from this reactor has been detected. Future work could involve both spectral and power studies of this system and a comparison with COSMOS 1176.

Other future nuclear spacecraft can be monitored with good sensitivity with the SMM gamma-ray spectrometer as long as it is kept operational.

VII. RECOMMENDATION

The lifetime of the Solar Maximum Mission is in doubt because of stabilization problems which have handicapped the capability of the pointed solar instruments. NASA may, because of budget restrictions, be forced to turn off SMM in the near future. The gamma-ray experiment is still functioning perfectly and is obtaining excellent data. It provides an excellent platform for studying any future satellites similar to COSMOS 1176 that may be launched in the next few years.

Should there be a need for future gamma-ray data it is recommended that DOD consider support for the continued operation of SMM in the event that NASA cannot.

VIII. ACKNOWLEDGMENTS

This work could not have been performed without the fine instrumentation built by the University of New Hampshire and Max Planck Institute under the funding and

auspices of NASA. Dr. D. Forrest is to be especially acknowledged. Here is a prime example of why it is important for basic research activities to be supported by the DOD. Serendipitous detections of this type are possible only with the continued development of technology which can service DOD as well as providing data of basic scientific value.

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